Physics 559: Quantum Devices

Syllabus

Fall 2024

Schedule: Tu-Thu 12:00 – 1:50 pm, KAP 138

Instructor: Eli Levenson-Falk

Office: SSC 222

Student hours: Mondays 2:00 – 3:00 pm

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Course Description

Physics 559 is a graduate-level course covering real-world quantum information hardware. It focuses mainly on superconducting electronics, covering design principles, single-qubit manipulation and measurement, multi-qubit operations, idealized and real-world performance, decoherence mechanisms, and novel directions. The course also surveys other hardware such as vacancy spins and quantum dots.

Learning Objectives

In this course you will learn the basics of implementations of quantum information hardware. You will learn the idealized versions of these devices and learn how they behave in real environments. The goal of this course is for students to become conversant in quantum hardware. To that end, you will learn:

- The principle of operation of different quantum devices, including how they are fabricated, manipulated, read out, and scaled.
- How to modify device parameters to achieve different performance.
- Noise processes affecting different devices, how to model noise's harmful impacts, and how they can be mitigated.
- Device applications including gate-based quantum computing, adiabatic quantum computing, analog quantum simulation, quantum communications, quantum sensing, and quantum measurement.

By the end of the course you will be familiar with the hardware challenges these implementations each face. You should then be able to quickly absorb and develop new applications for novel quantum hardware.

Course Assignments

The coursework will include 5 homework assignments and a student project. The assignments will draw on the material learned in class.

Description of Student Project

There are several options for a final project:

Option 1: QuBytes
The student writes 4 summaries of current quantum information research articles for the website QuBytes.org. These articles must have been first published (i.e., on arXiv) no more than 12 months earlier, and must focus on hardware. The professor must give prior approval of each article chosen. Summaries will be graded on accuracy of information (50%), clarity of writing (25%), and appropriateness of level (25%).

Option 2: SQuADDS
The student makes a significant contribution to the SQuADDS project codebase. The professor must give prior approval of the features added. As part of the contribution, the student must write documentation and an example code (or several) that takes advantage of the added feature, and demonstrate them running on a machine other than the student's own computer. Contributions will be graded on correct functionality (50%), impact (25%), and code and documentation readability (25%).

Option 3: QESim
The student writes 2-5 example lessons using QESim software. These lessons must illustrate concepts learned in the course. The professor must give prior approval of the lessons, including approving the number and scope. Lessons will be graded on correctness (50%), appropriateness of level (25%), and pedagogical value (25%).

Option 4: scqubits
The student writes 2-5 example lessons using the scqubits package. These lessons must illustrate concepts learned in the course. The professor must give prior approval of the lessons, including approving the number and scope. Lessons will be graded on correctness (50%), appropriateness of level (25%), and pedagogical value (25%).

Option 5: research proposal
Students will work in groups of 2-3 to create: (1) a proposal for an original type of quantum device; (2) a proposal for a novel application of an existing quantum device; (3) a proposal for a novel solution to / mitigation of a challenge facing an existing quantum device; (4) a quantitative description of the limits imposed on an existing quantum device by known noise processes; (5) another topic approved by the instructor. Some examples of possible projects include: a proposal for removing charge noise in a semiconductor qubit; a quantitative description of how altering spectral character of flux noise could improve a fluxonium qubit's coherence; a proposal for a magnetic gradient sensor using a trapped electron; a detailed review of a device not covered in the course.

Papers will take the form of a research proposal (similar to a qualifying exam document) of 10-20 pages including figures. Papers will be graded on novelty (40%), accuracy (40%), and presentation (20%).

Grading Breakdown

Course Element	% of Grade
Homework (5)	50%
Student Project	50%
TOTAL	100%

Assignment Submission Policy

Homeworks will be submitted in class on the assigned date or via Brightspace. Late homework will not be accepted except by prior approval of the instructor.

Grading Timeline

Strong effort will be made to grade and return homework within two weeks after it is received. Homework solutions will be posted on Blackboard.

Administrativia

A. Prerequisites

Quantum mechanics on the level of PHYS 438b or similar course. EE520 and EE514 will typically be considered adequate preparation even if no dedicated quantum mechanics course has been taken. Basic electricity and magnetism on the level of PHYS 152 or similar course is also required. Exceptions may be made to prerequisites; please contact the instructor.

Prior knowledge of basic programming will be an asset but not a requirement for this course. Likewise, knowledge of advanced E&M, Lagrangian and Hamiltonian mechanics, statistical mechanics, and solid state physics will be helpful but are not strictly required.

B. Disabilities

Students who need to request accommodations based on a disability are required to register each semester with the Disability Services and Programs. In addition, a letter of verification to the instructor from the Disability Services and Programs is needed for the semester you are enrolled in this course. If you have any questions concerning this procedure, please contact the course instructor and Disability Services and Programs at (213) 740-0776, STU 301.

C. Academic Integrity

Students who violate university standards of academic integrity are subject to disciplinary

sanctions, including failure in the course and suspension from the university. Since dishonesty in any form harms the individual, other students and the university, policies on academic integrity will be strictly enforced. The academic integrity guidelines can be found in

(i) The Trojan Integrity Guide,
http://www.usc.edu/student-affairs/SJACS/forms/tio.pdf
(ii) The Undergraduate Guide for Avoiding Plagiarism,
http:/www.usc.edu/student-affairs/SJACS/forms/tig.pdf

In plain language: don't cheat! Don't copy your answers from online, and don't post homework or problems online, don't use someone else's work. We have ways of determining who posted a problem, and if we catch you doing it then you'll be reported to OAI—no warnings, no second chances. I promise that you can get an excellent grade in this course if you do the work—just do the work!

A new note for this semester: ChatGPT really, really does not know much about cutting-edge research, which is what you'll be learning! If you try to pass off ChatGPT work as your own, you will: (1) get a bad grade because it does D+ level work at best; (2) get caught, because AI-generated content is quite easy to spot; and (3) get reported to OAI because I have no tolerance for this.

You also have signed something in the first week of class saying that you read the syllabus carefully in its entirety. So, since you're an honest person, you know to write the word "adiabaticity" in the "Other comments" field.

D. Classroom Behavior

Please be attentive, engaged, and relatively punctual in class. This is a small, seminar-style course so your participation is extremely important. We may take a whole class period to discuss a single concept and build an intuitive model where one hasn't existed before!

Any student who wants to learn about quantum devices belongs in this course. It my job and yours to ensure that this welcoming messages is felt by all students. Questions, discussion, and general interaction are strongly encouraged at all times. Hostile or unwelcoming comments or behaviors are always unacceptable and will be addressed appropriately.

E. Faculty Liaison

All courses in the Department of Physics & Astronomy have an assigned Student Ombuds to serve students as a confidential, neutral, informal, and independent resource when they wish to discuss issues concerning their course without directly confronting their instructor. The Faculty Liaison for this course is Prof. Jack Feinberg (feinberg@usc.edu, 213-740-1134, SSC 327). Note that the Faculty Liaison is a mandatory reporter for potential harm to self or others, sexual assault, and other such issues; for fully confidential discussion of these issues, please speak with the Counseling and Mental Health department.

F. Statement for observance of religious holidays

USC's policy grants students excused absences from class to observe religious holidays: http://orl.usc.edu/life/calendar/absences/. In this case, please contact your instructor in advance to agree on alternative course requirements.

G. Support Systems

Counseling and Mental Health - (213) 740-9355 – 24/7 on call

studenthealth.usc.edu/counseling

Free and confidential mental health treatment for students, including short-term psychotherapy, group counseling, stress fitness workshops, and crisis intervention.

National Suicide Prevention Lifeline - 1 (800) 273-8255 – 24/7 on call

suicidepreventionlifeline.org

Free and confidential emotional support to people in suicidal crisis or emotional distress 24 hours a day, 7 days a week.

Relationship and Sexual Violence Prevention and Services (RSVP) - (213) 740-9355(WELL), press "0" after hours – 24/7 on call

studenthealth.usc.edu/sexual-assault

Free and confidential therapy services, workshops, and training for situations related to gender-based harm.

Office of Equity and Diversity (OED)- (213) 740-5086 | Title IX – (213) 821-8298

equity.usc.edu, titleix.usc.edu

Information about how to get help or help someone affected by harassment or discrimination, rights of protected classes, reporting options, and additional resources for students, faculty, staff, visitors, and applicants. The university prohibits discrimination or harassment based on the following *protected characteristics*: race, color, national origin, ancestry, religion, sex, gender, gender identity, gender expression, sexual orientation, age, physical disability, medical condition, mental disability, marital status, pregnancy, veteran status, genetic information, and any other characteristic which may be specified in applicable laws and governmental regulations. The university also prohibits sexual assault, non-consensual sexual contact, sexual misconduct, intimate partner violence, stalking, malicious dissuasion, retaliation, and violation of interim measures.

Reporting Incidents of Bias or Harassment - (213) 740-5086 or (213) 821-8298

usc-advocate.symplicity.com/care_report

Avenue to report incidents of bias, hate crimes, and microaggressions to the Office of Equity and Diversity |Title IX for appropriate investigation, supportive measures, and response.

The Office of Disability Services and Programs - (213) 740-0776

dsp.usc.edu

Support and accommodations for students with disabilities. Services include assistance in providing readers/notetakers/interpreters, special accommodations for test taking needs, assistance with architectural barriers, assistive technology, and support for individual needs.

USC Support and Advocacy - (213) 821-4710

uscsa.usc.edu

Assists students and families in resolving complex personal, financial, and academic issues adversely affecting their success as a student.

Diversity at USC - (213) 740-2101

diversity.usc.edu

Information on events, programs and training, the Provost's Diversity and Inclusion Council, Diversity Liaisons for each academic school, chronology, participation, and various resources for students.

USC Emergency - UPC: (213) 740-4321, HSC: (323) 442-1000 – 24/7 on call

dps.usc.edu, emergency.usc.edu

Emergency assistance and avenue to report a crime. Latest updates regarding safety, including ways in which instruction will be continued if an officially declared emergency makes travel to campus infeasible.

USC Department of Public Safety - UPC: (213) 740-6000, HSC: (323) 442-120 – 24/7 on call

dps.usc.edu

Non-emergency assistance or information.

Tentative Course Schedule

WEEK	TOPIC	READINGS

1	Overview of quantum hardware; required tools in quantum mechanics and E&M	TBA
2	Circuit quantization, circuits and resonance; transmon qubits	Boehm thesis Ch. 1-2 "A Quantum Engineer's Guide To Superconducting Circuits" Sections I & II
3	Transmons con't; charge, flux, and phase qubits (Homework 1 due)	Schuster thesis, Ch. 1-3
4	Single-qubit gate theory, practice, and experimental implementation; gate errors	"A Quantum Engineer's Guide To Superconducting Circuits" Section IV
5	2 qubit gate theory, practice, and experimental implementation; gate errors (Homework 2 due)	"A Quantum Engineer's Guide To Superconducting Circuits" Section IV "Operation and intrinsic error budget of a two-qubit cross-resonance gate" (Tripathi et al.), Section I, II, IIIA, V
6	2 qubit gates con't	"Demonstration of a High-Fidelity CNOT for Fixed-Frequency Transmons with Engineered ZZ Suppression" (Kandala et al.)
7	Qubit readout; dispersive measurement (Homework 3 due) (fall break Thursday)	"A Quantum Engineer's Guide To Superconducting Circuits" Section V
8	Qubit readout con't, parametric amplifiers; decoherence mechanisms	"Observation of high coherence in Josephson junction qubits measured in a three-dimensional circuit QED architecture" (Paik et al.)
9	Decoherence mechanisms continued (Homework 4 due)	"UCSB final report for the CSQ program: Review of decoherence and materials physics for superconducting qubits"
10	Software and tools: scqubits, SQuADDS, QESim	TBA
11	Nanofabrication and packaging (Homework 5 due)	Slichter thesis Ch. 4 "Microwave Package Design for Superconducting Quantum Processors" (Huang et al.)
12	Measurement and control electronics; cryogenics (Final project topics and groups proposed)	"Principles of Dilution Refrigeration"
13	Fluxonium qubits	Nguyen Thesis Ch. 4
14	Fluxonium continued (Thanksgiving break) (Final project topics and groups finalized)	"Blueprint for a High-Performance Fluxonium Quantum Processor"
15	Novel architectures—0-pi, trimon, blochnium, cavity qubits, etc.	"Experimental realization of an intrinsically error-protected superconducting qubit"